Atmospheric & Space Technology Research Associates LLC
www.astraspace.net

Ensemble Assimilation Using First-Principles Models: A Tool for Three-Day Space Weather Forecasts

Space Weather Workshop, 2015

April 16th, 2015

G. Crowley[1], M. Pilinski[1], J. Wolfe[1], T. Fuller-Rowell[2], T. Matsuo[2], S. Solomon[3], L. Qian[3], J. Thayer[4], M. Codrescu[5]

[1]ASTRA LLC., [2]CIRES. [3]UCAR, [4]U. of Colorado, [5]NOAA

ASTRA: Space Weather Focus

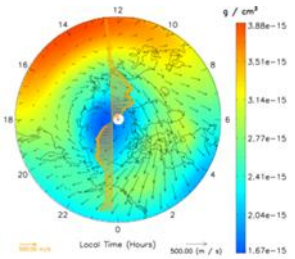
❖Science
❖ Technology
❖ Applications
Bringing It All Together

ASTRA

Modeling

Physics-Based Modeling (TIMEGCM)

Real-Time Specification of Ionosphere/ Thermosphere



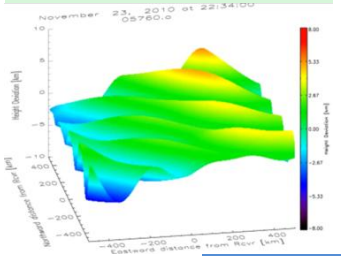
Data Assimilation

High-latitude Electrodynamics

Global Ionosphere

Thermospheric Neutral Density

Satellite Drag & Ballistic Coefficients



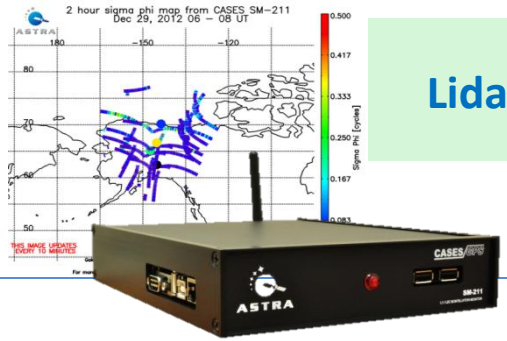
Data Services

Space Based Data

Ground Based Data

Forensic Space Weather Analysis

Space weather Phone Apps



Ground-based Instrument Development

GPS-based Space Weather Monitor

E-fields and Magnetometers

Low Power Ionospheric Sounder

HF TID Mapper

Lidar Systems

Space Systems

CubeSat Missions
- NSF: DICE & LAICE
- AF: DIME, SIPS & TSS
- NASA: SORTIE & MiRaTa

Plug-N-Play Avionics

CubeSat Instruments
- Scanning UV Photometer
- E-field Double Probe
- RF Waves & Sounder
- Wind Profiler
- GPS-based Space Weather Monitor
- Magnetometer & Langmuir Probe

Satellite Aerodynamics

ASTRA • www.astraspace.net
303-993-8039 • solutions@astraspace.net

Introduction

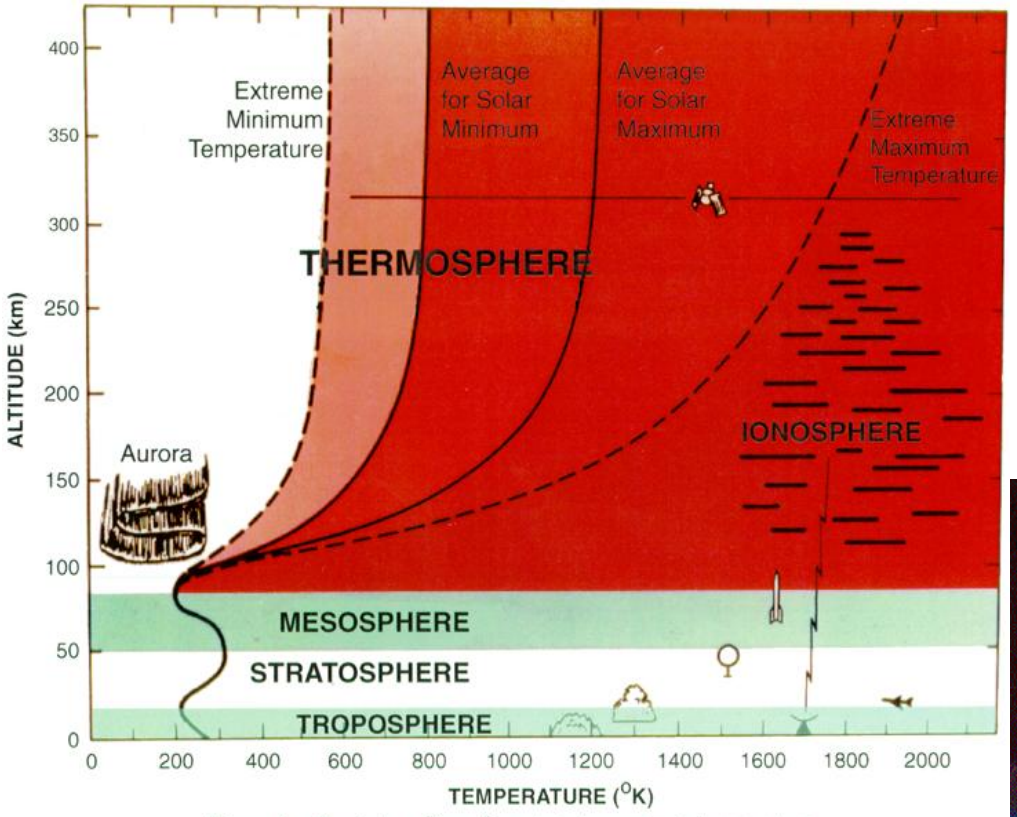
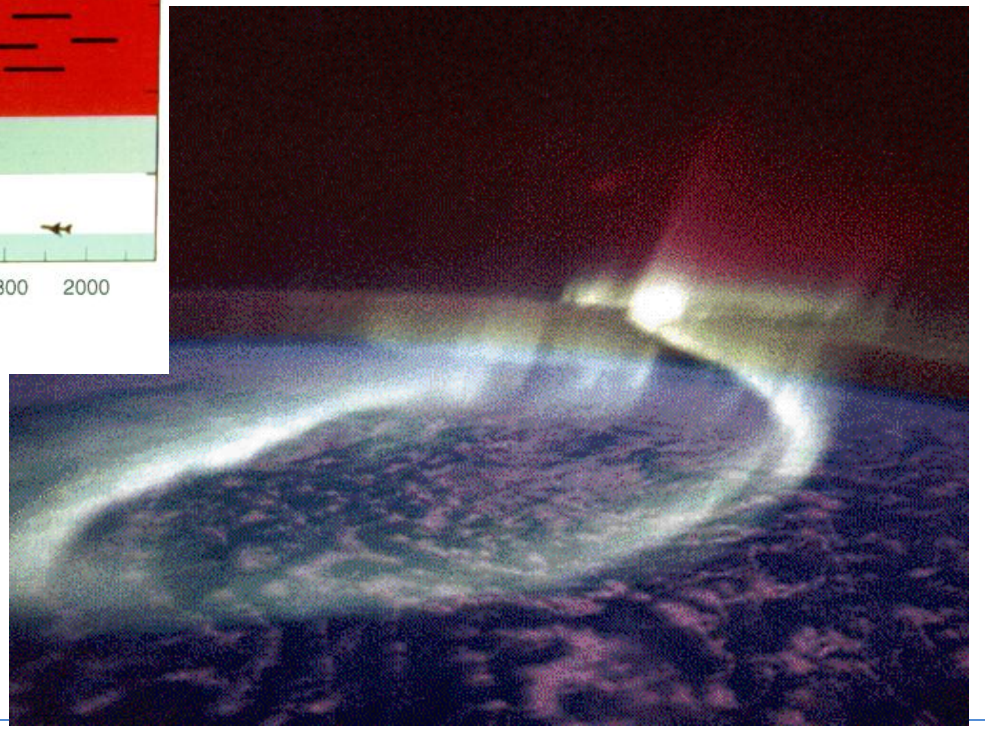


Figure 1c: Typical profiles of neutral atmospheric temperature



Introduction

❖Science
❖ Technology
❖ Applications
Bringing It All Together

ASTRA

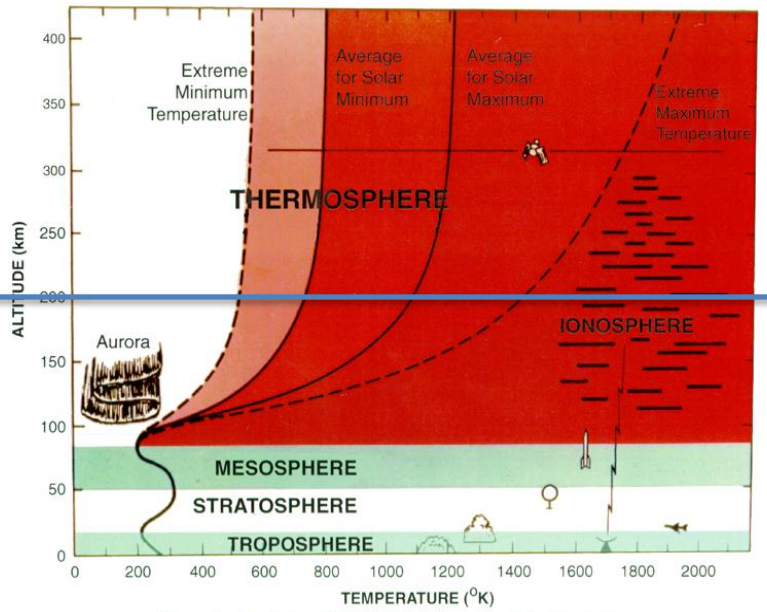
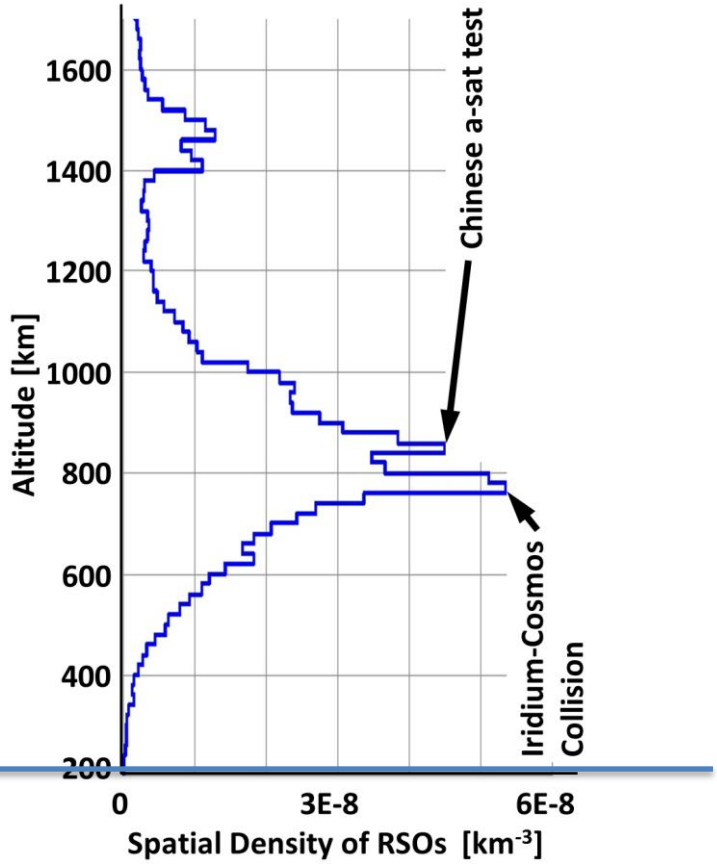


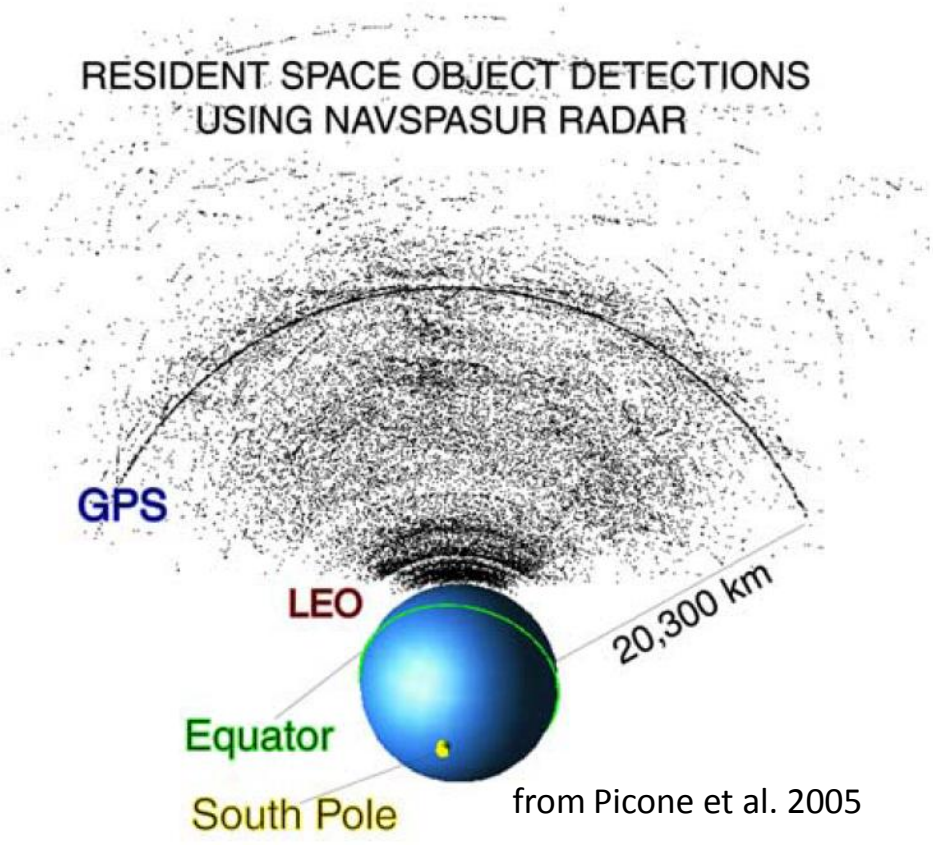
Figure 1c: Typical profiles of neutral atmospheric temperature



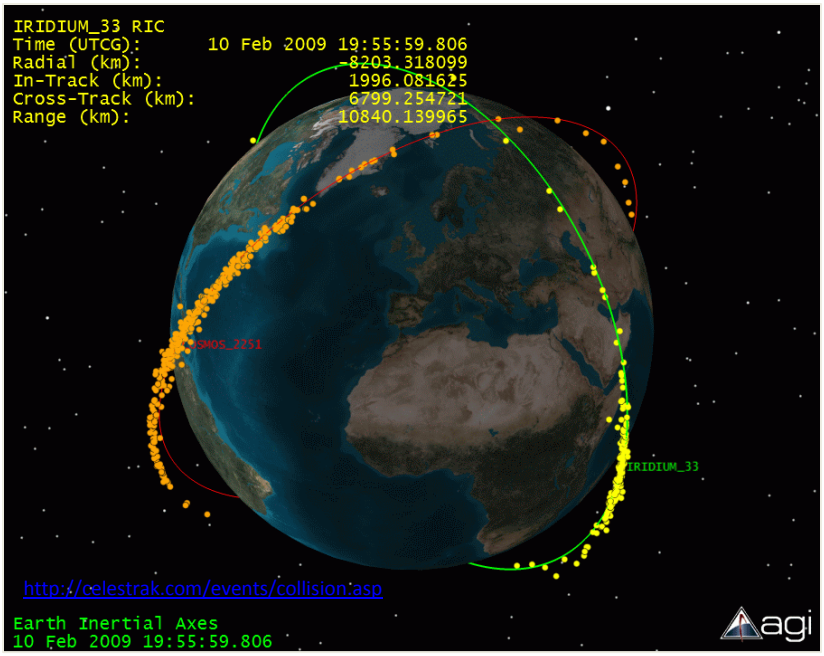
Who cares about satellite drag?

Satellite drag errors degrade capability to:

- Maintain accurate catalog of all space objects
- Predict and avoid space collisions
- Predict satellite reentry time & location



from Picone et al. 2005



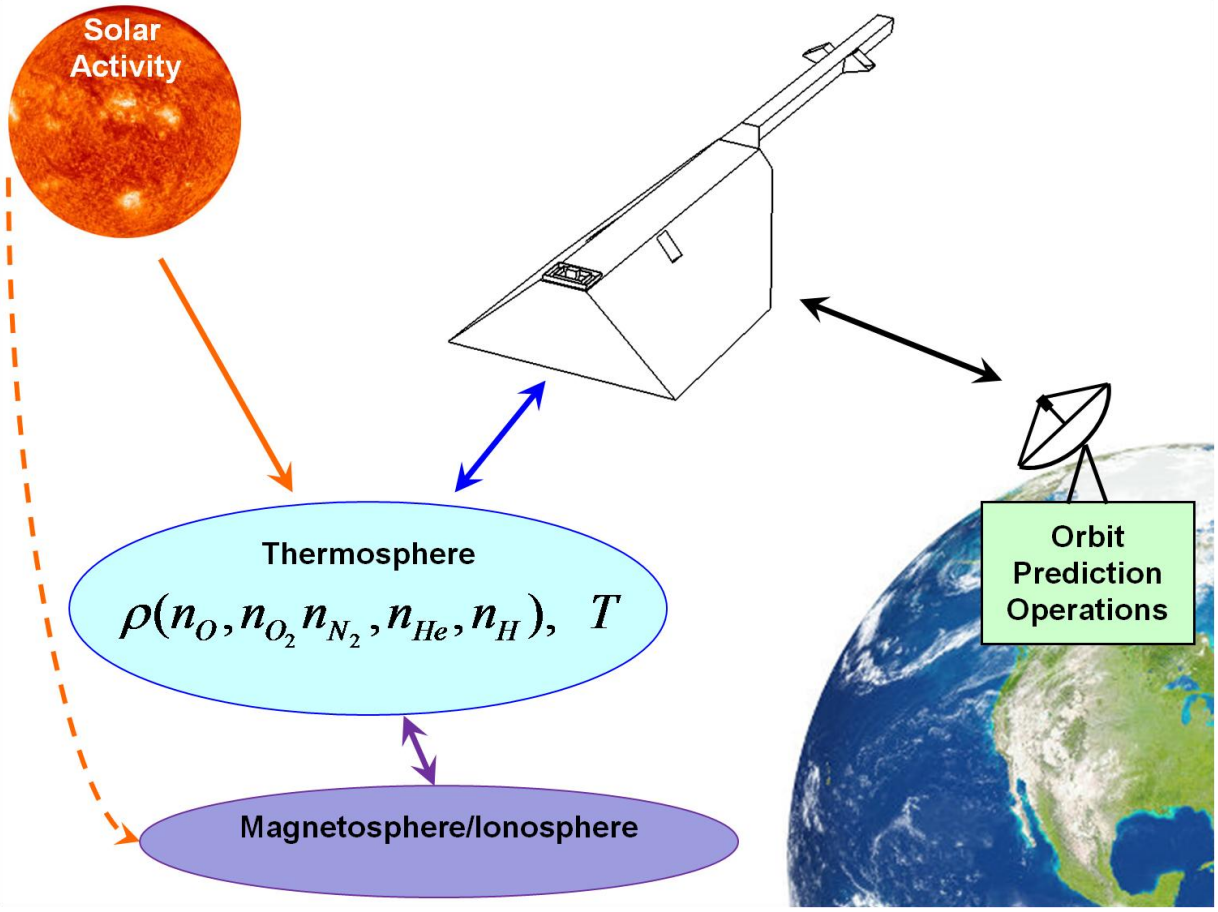
What is Satellite Drag?

Direct Atmospheric Impacts

- Density = f(Temp, Composition)
- Winds

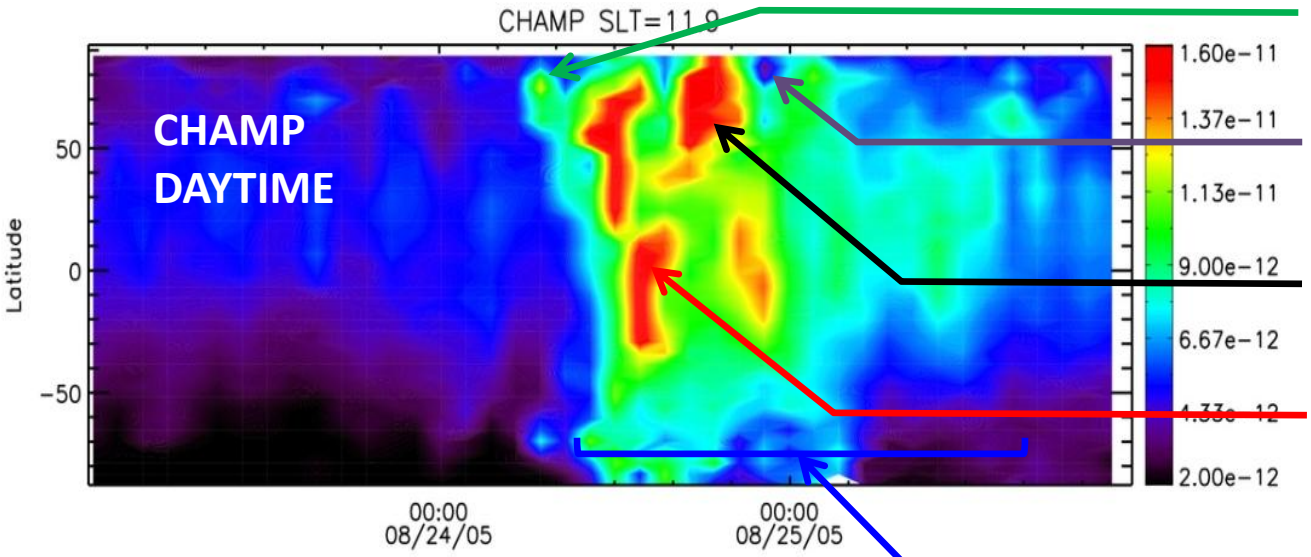
Indirect Atmospheric Impacts (through force coefficient)

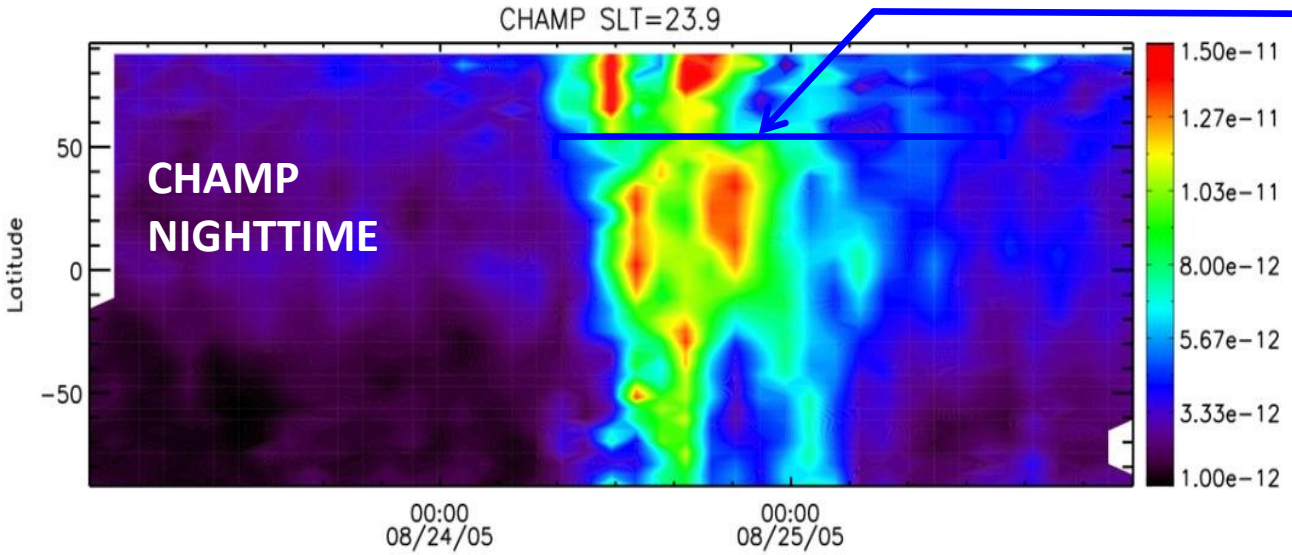
- Composition
- Temperature
- Winds
- Mean-Free Path



$$a_D = -\frac{1}{2}\frac{C_D\left(T_a, V, \lambda, n_O, n_{N_2}, \ldots, n_H\right)A}{m}\rho\left(T_a, n_{N_2}, \ldots, n_H\right)V^2$$

Density Perturbations at 400 km





Cusp Density 0740 UT

Density "hole" 20-24 UT

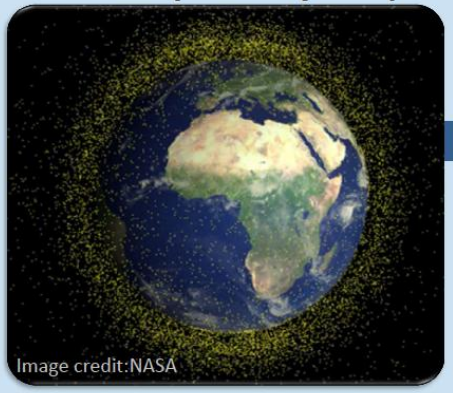
2nd Poynting Flux Event 16-20 UT

Gravity Wave Propagation

Global Density Enhancement lasting many hours (orbits)

ADAM Overview and Benefits

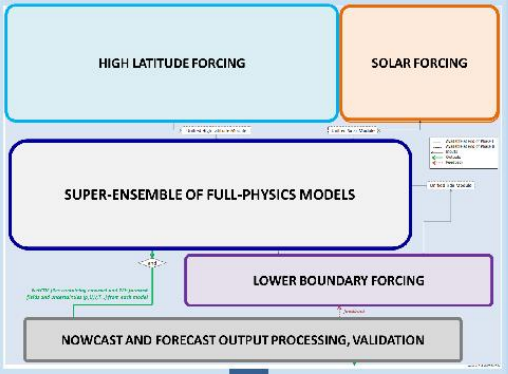
Resident Space Objects (LEO)



satellite drag and density observations

- ***Orbit observations***
- *GPS*
- *Accelerometers*
- *O/N_2*
- *Mass Spectrometer*

ADAM Architecture



orbital analysis

Atmospheric
Density
Assimilation
Model

Super-Ensemble Approach

Image credit: TerraMetrics, Google

Output information feeds into existing orbit prediction and determination tools

conjunction analysis

Results

- Improved satellite orbit nowcast and 72h forecast
  - Improvements over HASDM and JB08
  - Up to three-fold improvement during storms and solar minimum
- Densities, winds, and composition outputs
- Covers altitudes from 30 km to 1500 km
- Improved performance during geomagnetic storms

Requirements

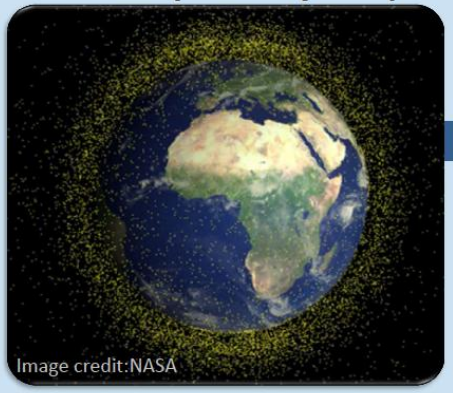
	Requirement	Goal
Nowcast	Outperform JB08 *JB08: 7-18% at 200-800km*	Outperform HASDM (Jacchia '70, with 60-90 objects) *HASDM: 6-10% at 200-800km*
72h Forecast	Outperform JB08 in forecast mode	Outperform HASDM in forecast mode

ADAM Overview and Benefits

❖Science
❖ Technology
❖ Applications
Bringing It All Together

ASTRA

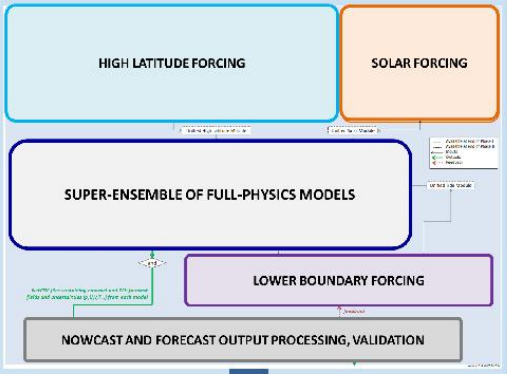
Resident Space Objects (LEO)



satellite drag and density observations

- ***Orbit observations***
- *GPS*
- *Accelerometers*
- *O/N_2*
- *Mass Spectrometer*

ADAM Architecture



orbital analysis

Atmospheric
Density
Assimilation
Model

Super-Ensemble Approach

Image credit: TerraMetrics, Google

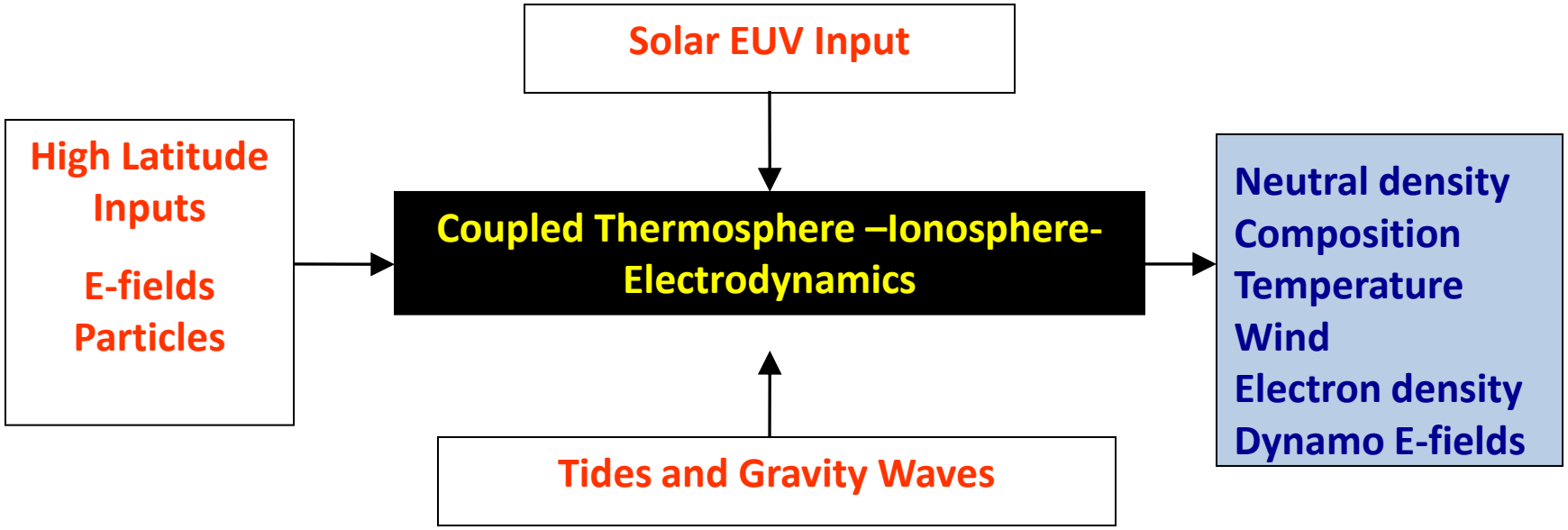
Output information feeds into existing orbit prediction and determination tools

conjunction analysis

Results

- Improved satellite orbit nowcast and 72h forecast
  - Improvements over HASDM and JB08
  - Up to three-fold improvement during storms and solar minimum
- Densities, winds, and composition outputs
- Covers altitudes from 30 km to 1500 km
- Improved performance during geomagnetic storms

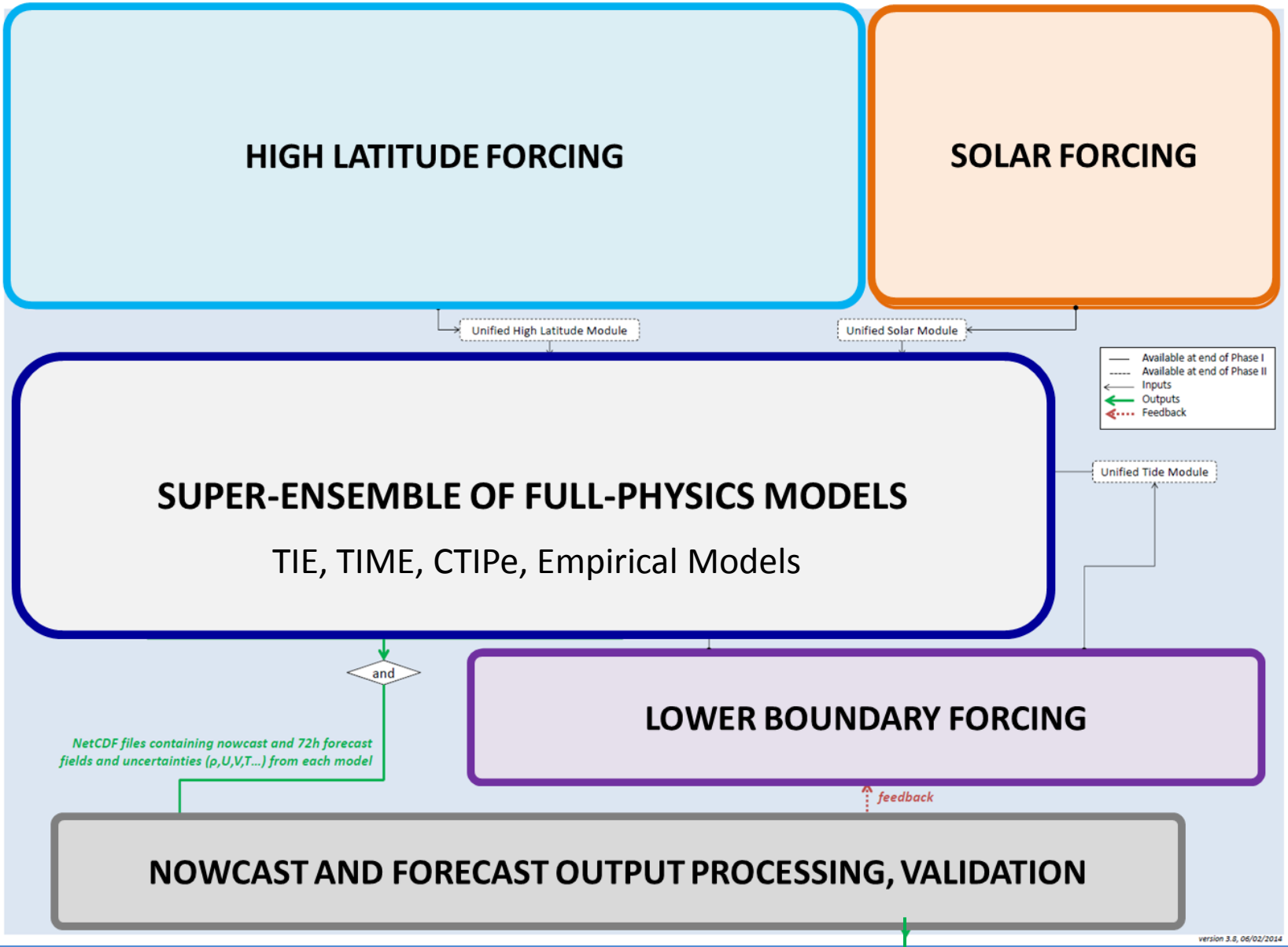
Important Inputs to the Thermosphere – Ionosphere System



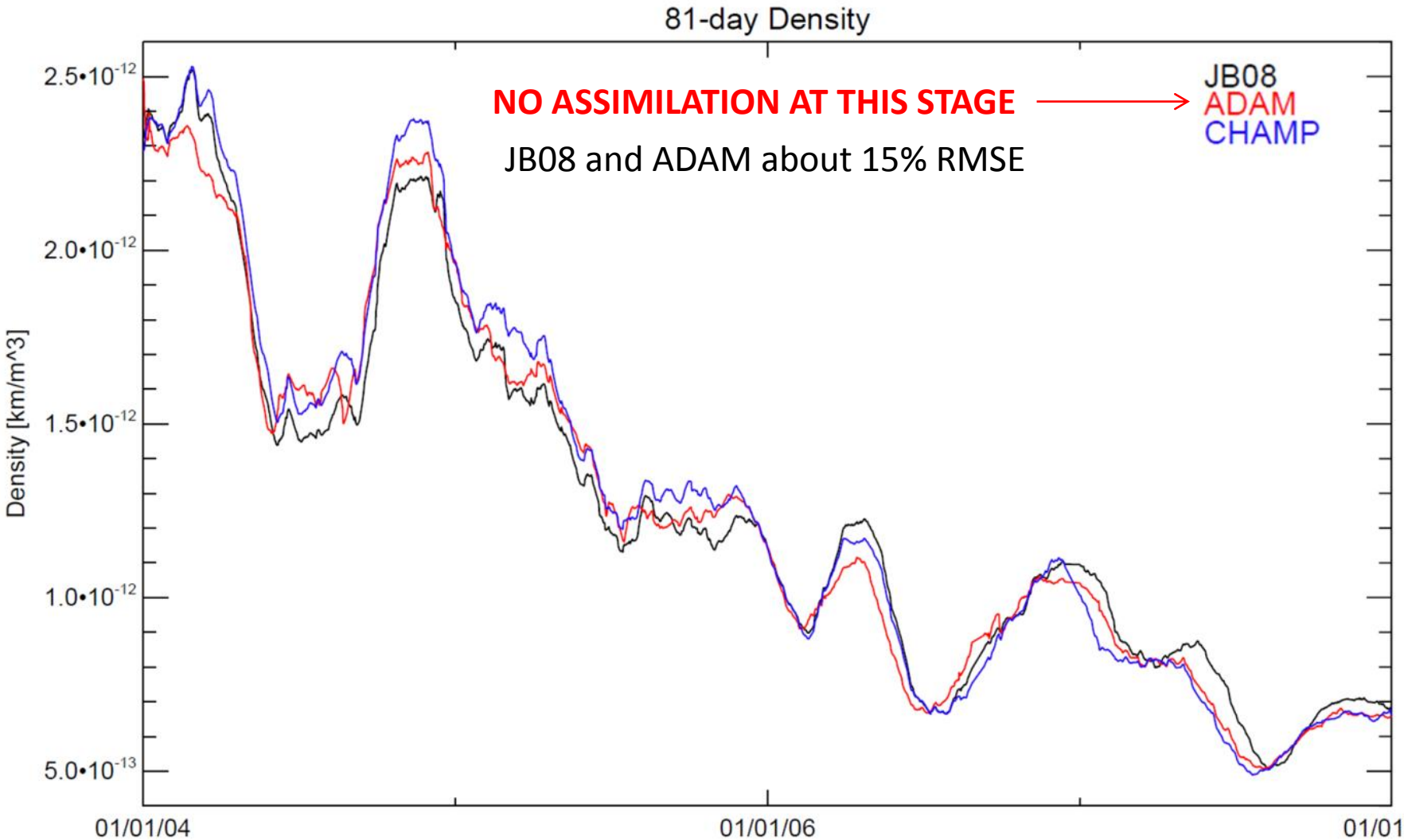
ADAM top level design

❖Science
❖ Technology
❖ Applications
Bringing It All Together

ASTRA

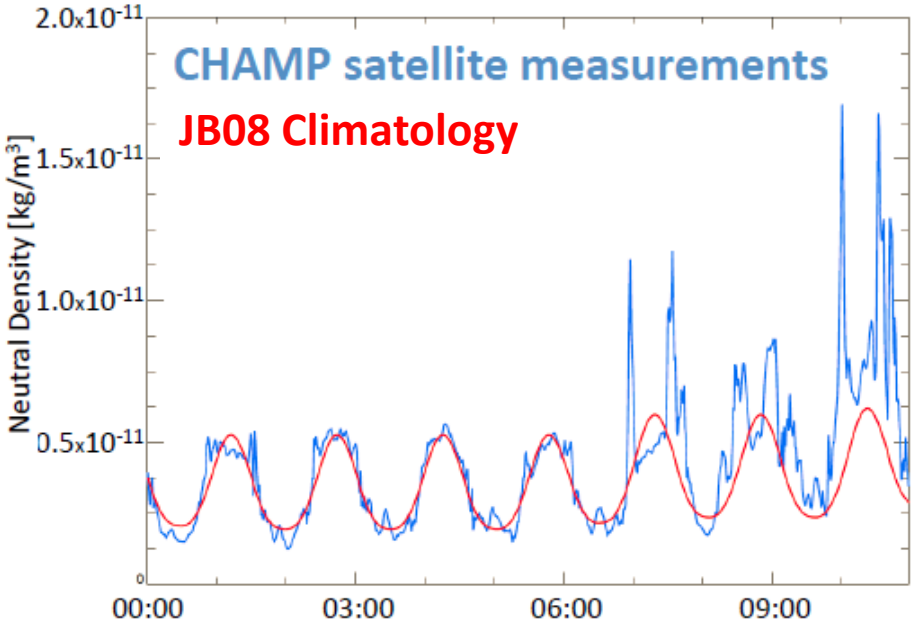


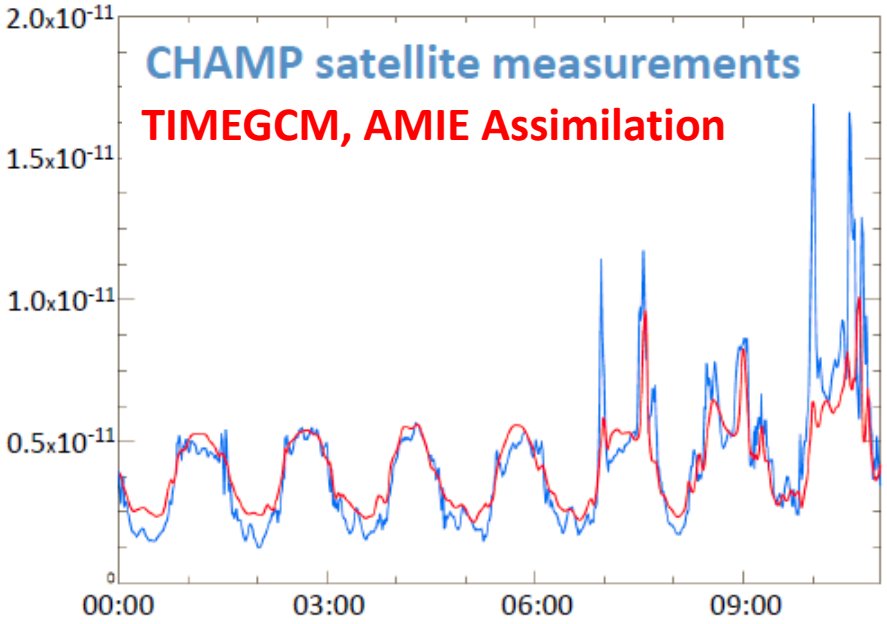
Feasibility



JB08 and CHAMP densities compared with best performing model in super-ensemble of full-physics members (based on 40-day trailing average)

Feasibility: storm response modeling





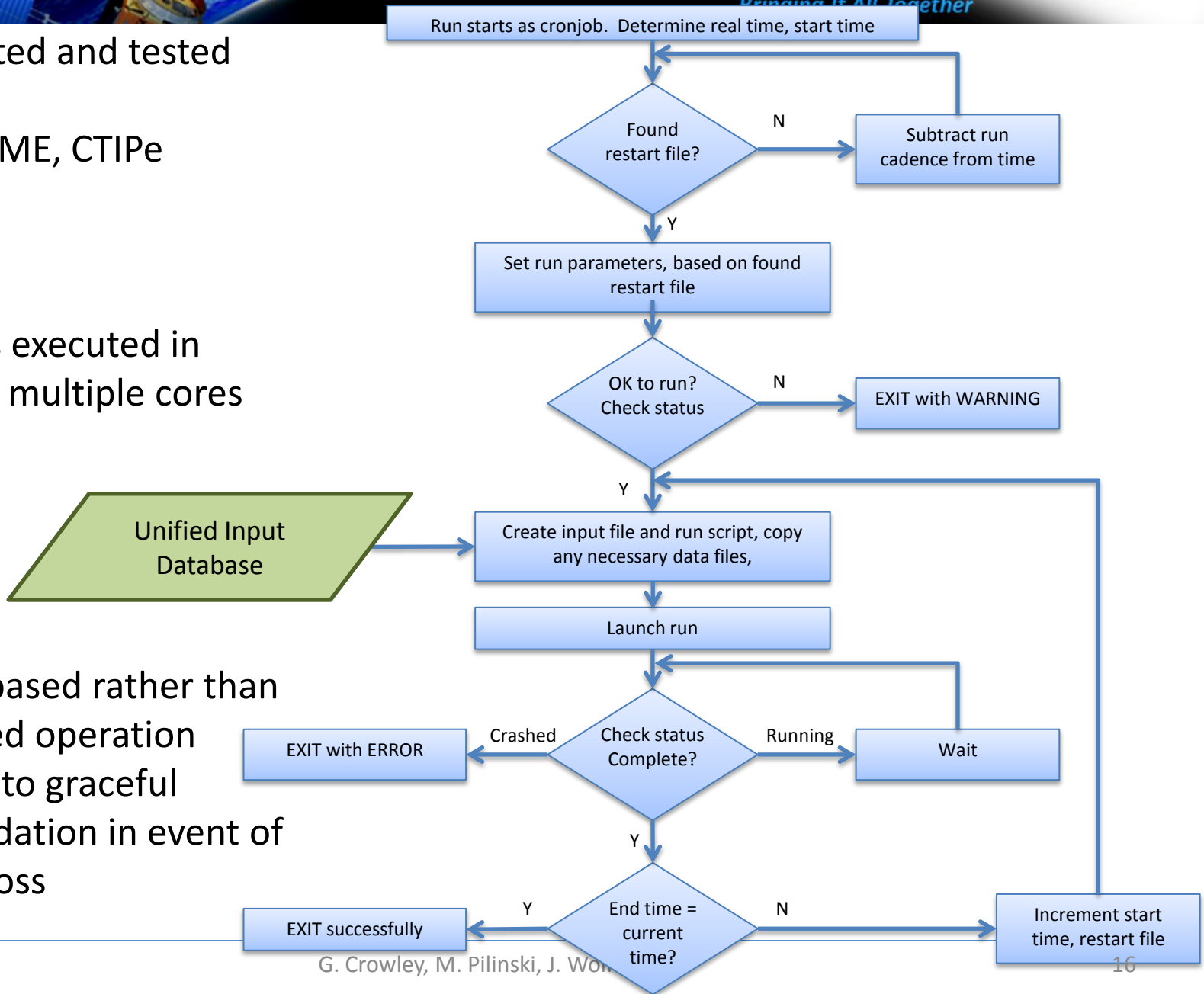
Improvements in neutral density when high-latitude electric fields are specified using assimilated electric fields

Design Features

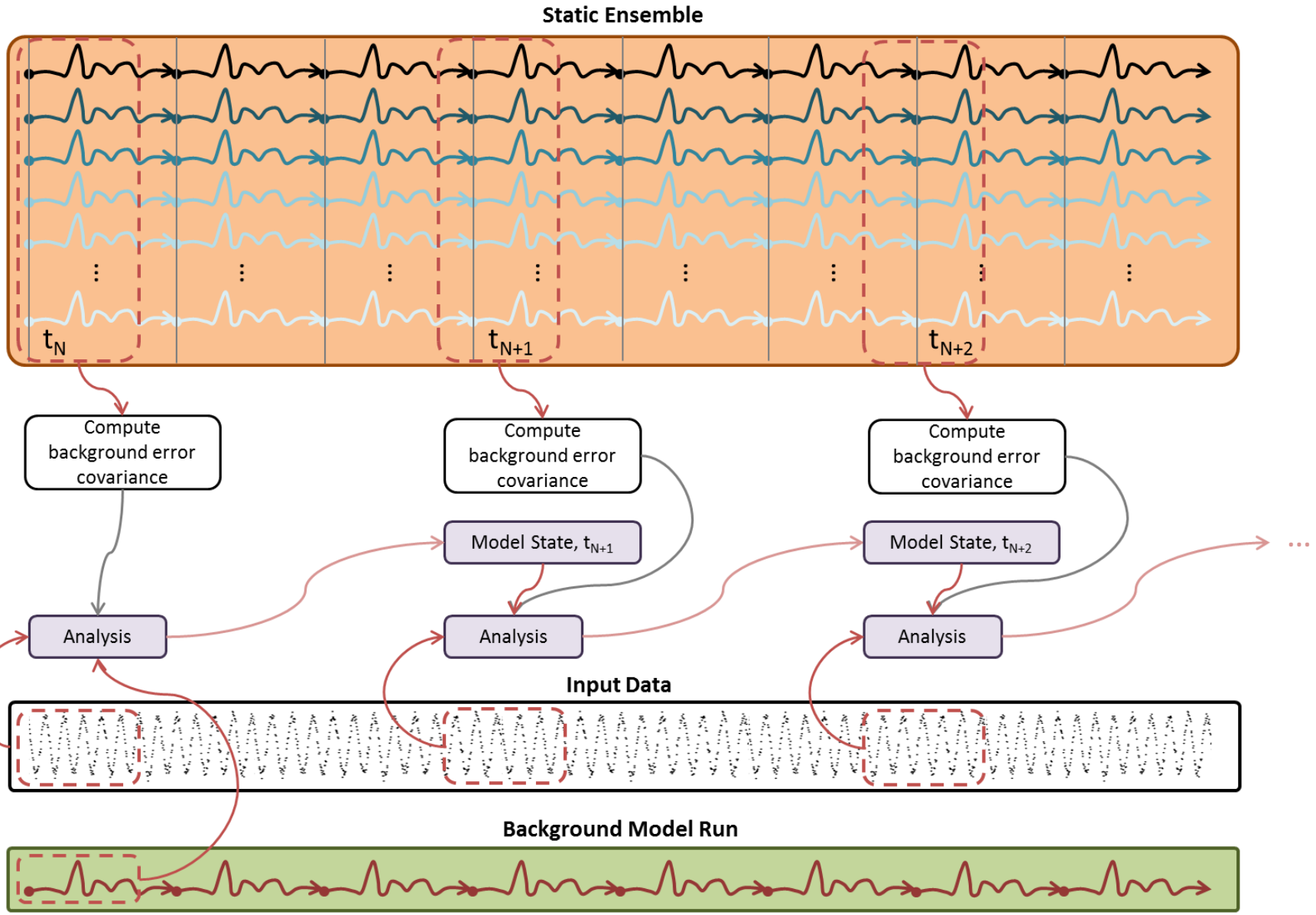
- Multiple model (super-ensemble) approach
- Dynamically tuned models result in optimum background atmospheric state
- Data Assimilation
- Graceful degradation in case of input-stream or model interruption
- Inclusion of TIME-GCM allows for specification of densities in the re-entry regime, down to 30km
- Inclusion of Helium in several models allows for drag computation up to 1500km

Architecture for Realtime Ensemble Runs

- Implemented and tested with:
  - TIE, TIME, CTIPe
- Ensembles executed in parallel on multiple cores
- Schedule based rather than event based operation
  - Leads to graceful degradation in event of data-loss



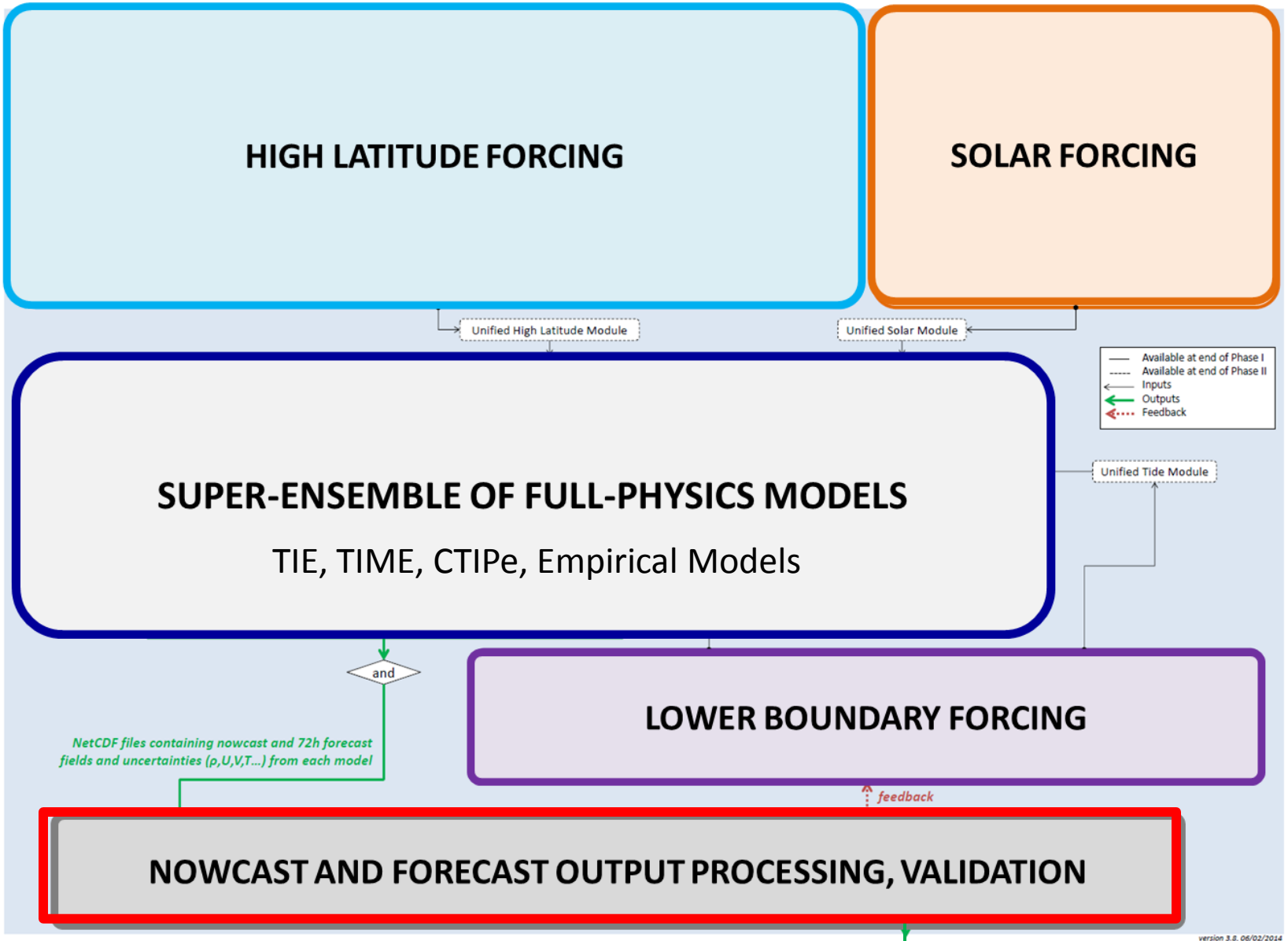
Assimilation
Optimal Interpolation (OI)



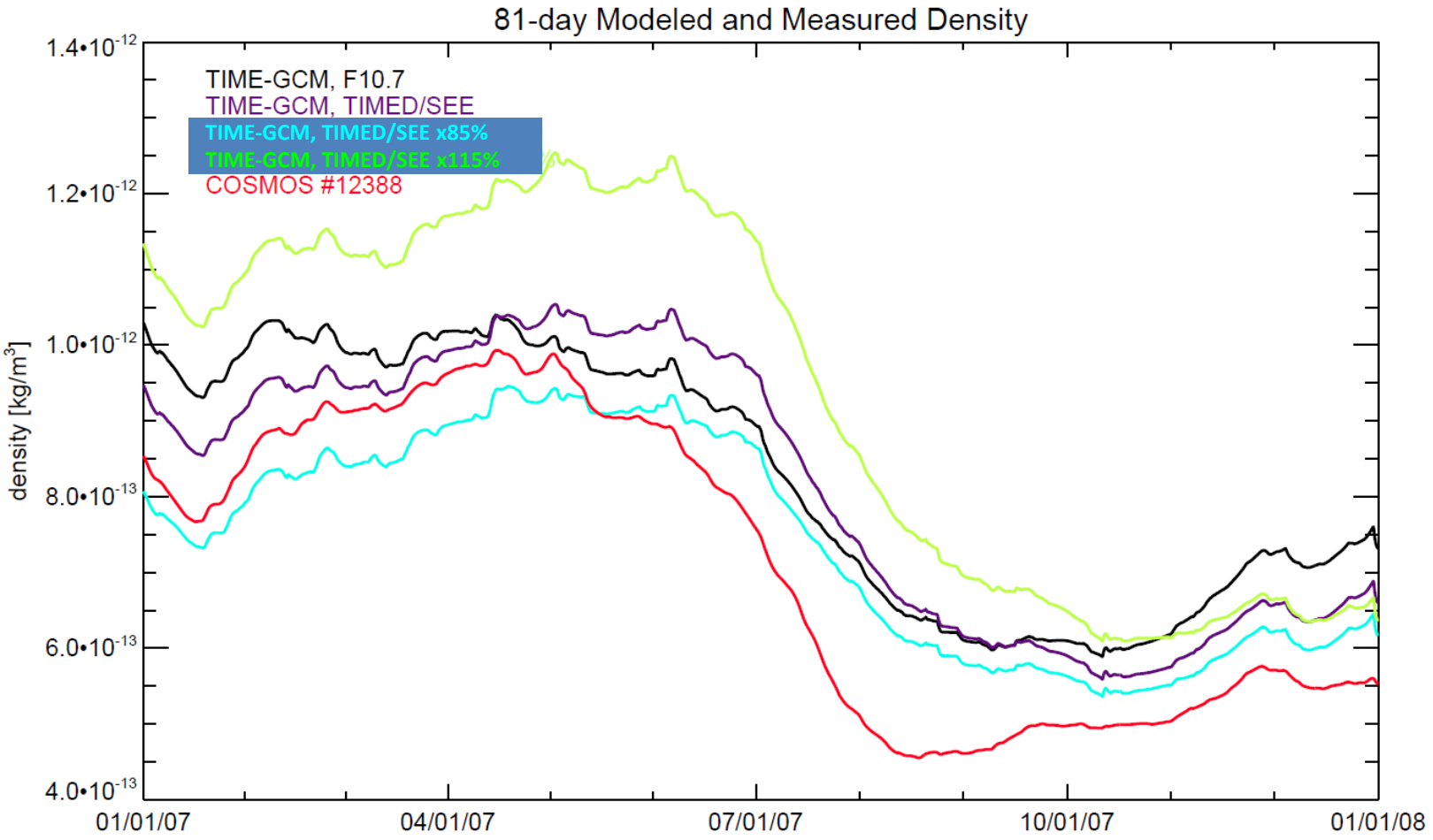
ADAM top level design

❖Science
❖ Technology
❖ Applications
Bringing It All Together

ASTRA



Realtime Ensemble Tests

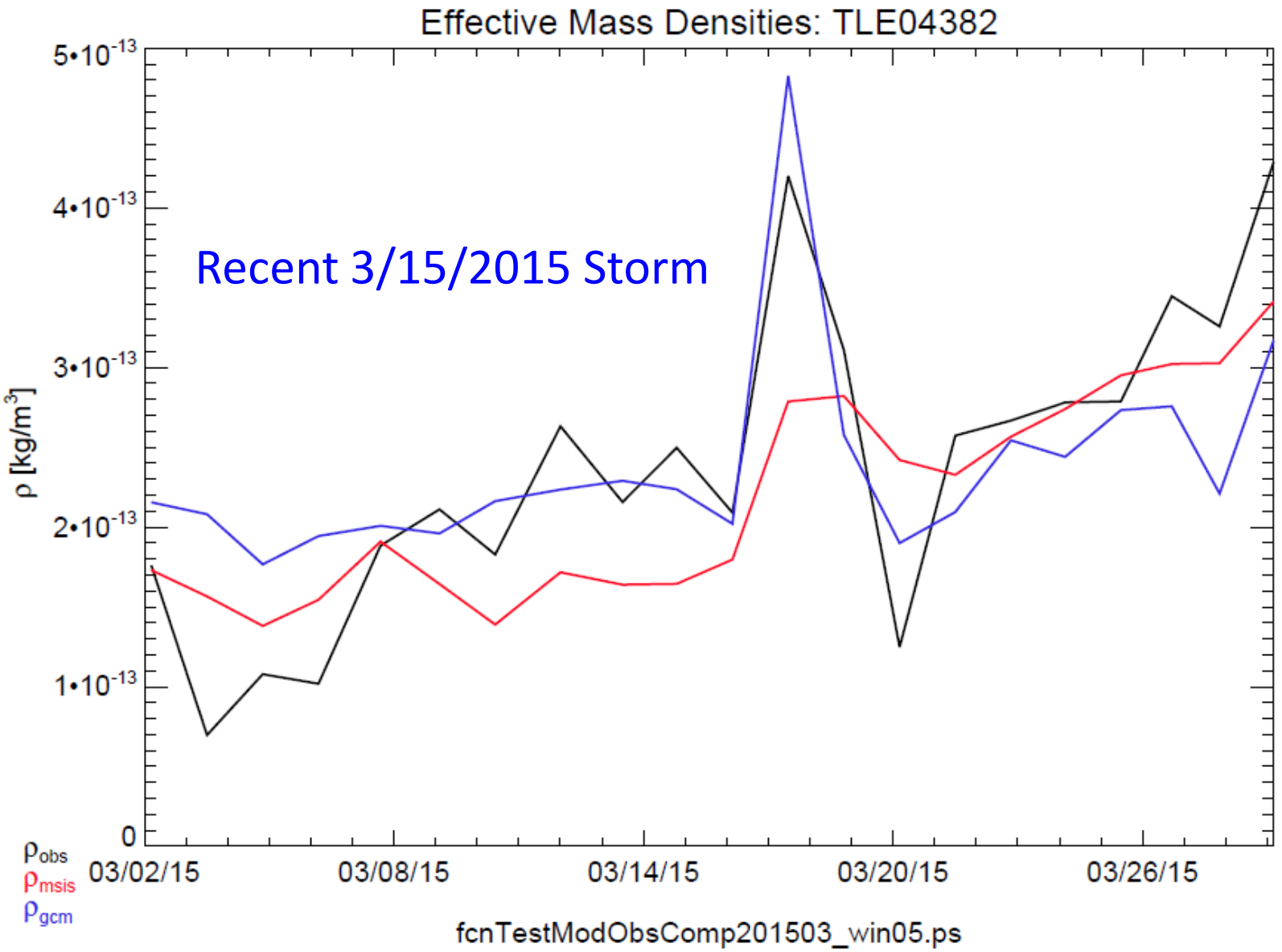


Testing with TLE data

- TLE's are being used as a stand in for orbital arcs analysis
  - Cadence and arc length is a conservative stand-in for the special-perturbations approach available operationally to the customer
  - Will transition to 6-hour arcs from special perturbations analysis in Phase III

- Temporary Drawbacks
  - Lower signal-to-noise
  - Latency (~1 day)

Orbit Average Drag Measurement
DFH-1



Options for additional inputs

Assimilated Data Types

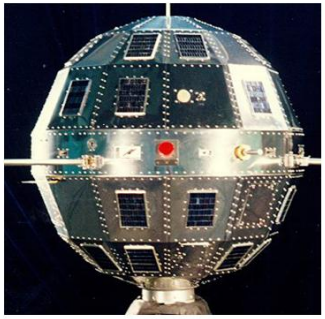
Data Type	Assimilation Time Span	Notes
Orbit Average Drag i.e. Calspheres, DANDE, POPACS	6-72 h	Infer observed energy dissipation rate (EDR) from general perturbations (TLEs) or special perturbations (high task tracking data). Select 30-90 objects with stable ballistic coefficients.
Orbit Average Densities	24 hours	Already processed high-task tracking data
Orbit Resolved Drag: GPS	15-30 min	Observed EDR from special perturbations and GPS measurements
Orbit Resolved Drag: accelerometers (Swarm)	15 min	Observed acceleration at 10-45 sec cadence (in-track and cross-track), binned to 15 min
O/N2 (GOLD, DMSP-SSUSI)	30 min	Dayside disk composition
Mass Spectrometer	10-30 sec	In-situ day and night composition

Dynamic Calibration from Observations of Satellite Orbits

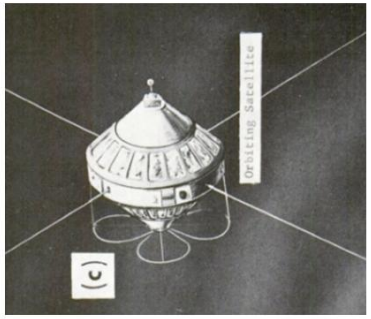
❖Science
❖ Technology
❖ Applications
Bringing It All Together

ASTRA

VANGUARD II



DFH-I

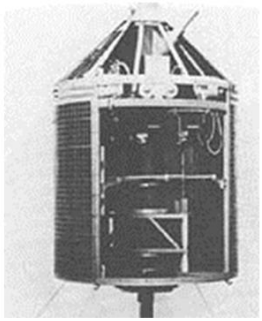


EXPLORER VII

DANDE

POPACS 1, 2, 3

RIGIDSPHERE 2



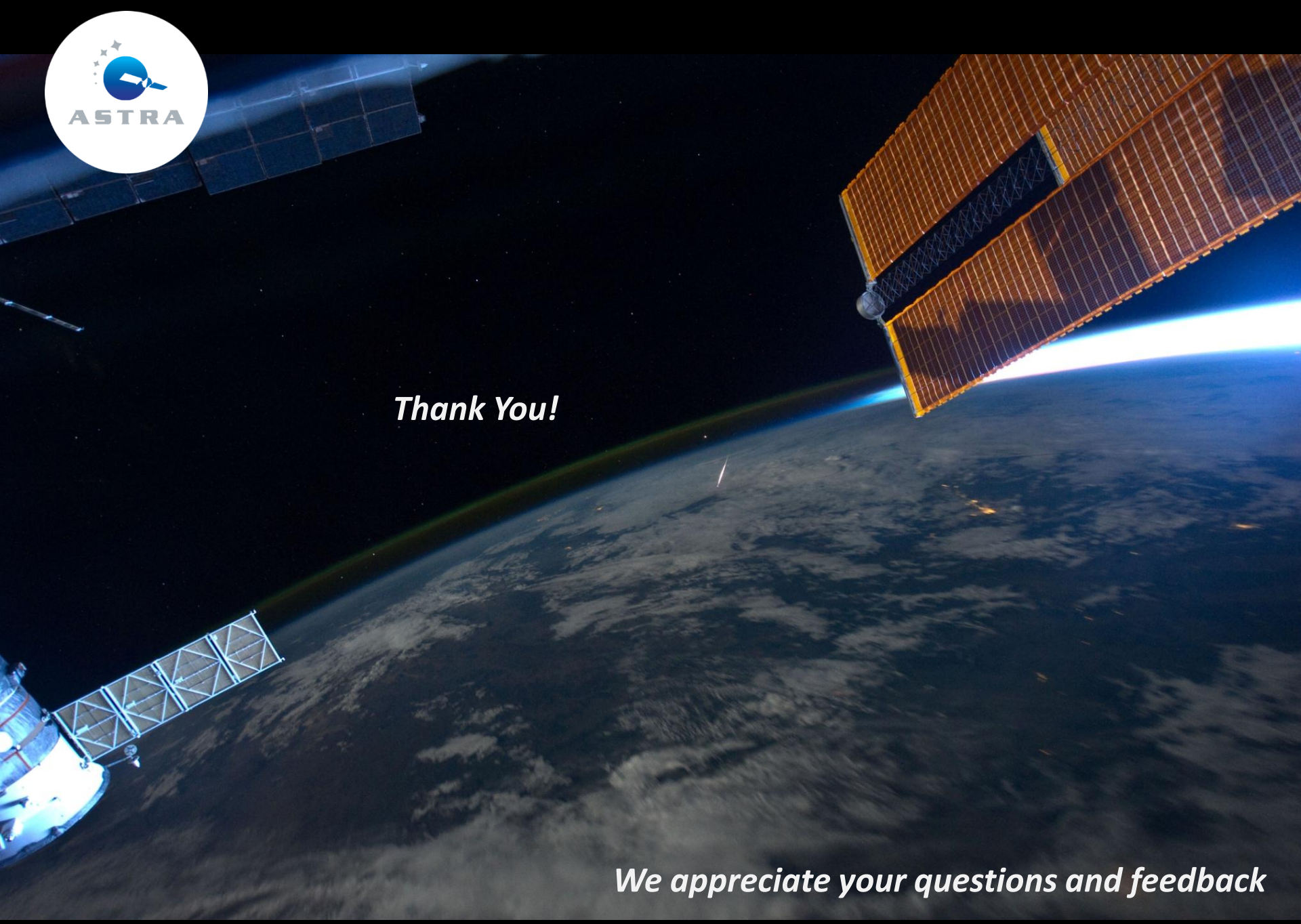
AZUR (GRS A)

PAM-D (left), SL-3 (center), SL-8 (right) rocket body outlines, shown to scale

190 – 900 km altitude, ±90° latitude coverage

SUMMARY

- New state-of-the-art assimilative model of the thermosphere is being developed
- Include many of the lessons learned from NADIR MURI project (funded by AFOSR)
- 1st year into a 2-yr project
- Expected to meet AF goals and requirements for specifying satellite drag
- Future plans to make outputs commercially available to civilian customers


ASTRA
Thank You!
We appreciate your questions and feedback

What is Satellite Drag?

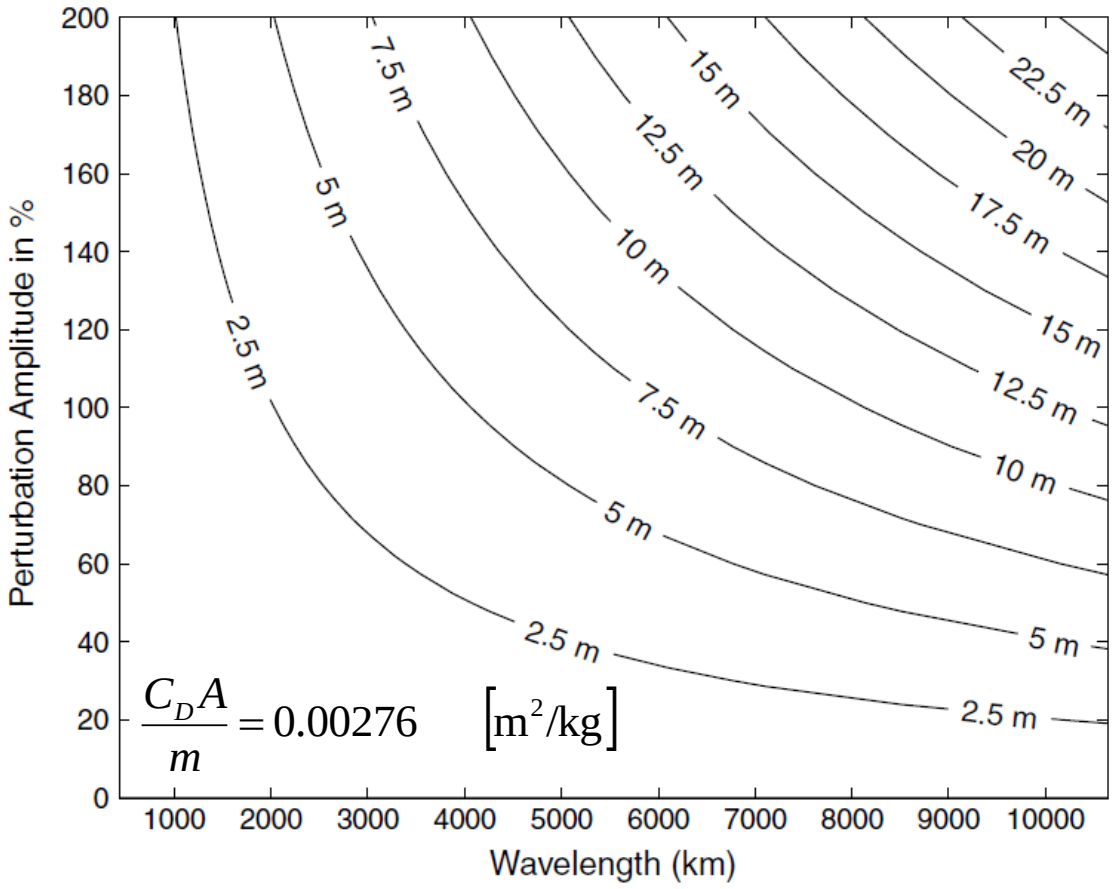
Relative importance of various scales

- Large scale perturbations can be misrepresented in empirical models
- It takes long-wavelength perturbations to cause significant position errors
- 3U sun-pointing CubeSat

$$\frac{C_D A}{m} \approx 0.02 \quad \left[\mathrm{m}^2/\mathrm{kg}\right]$$

- 100m errors are considered "significant" by USAF at 400 km altitude [Anderson et al. 2008]

24 Hour Orbital In-Track Error at 400km Circular Orbit



[Anderson et al. 2009]

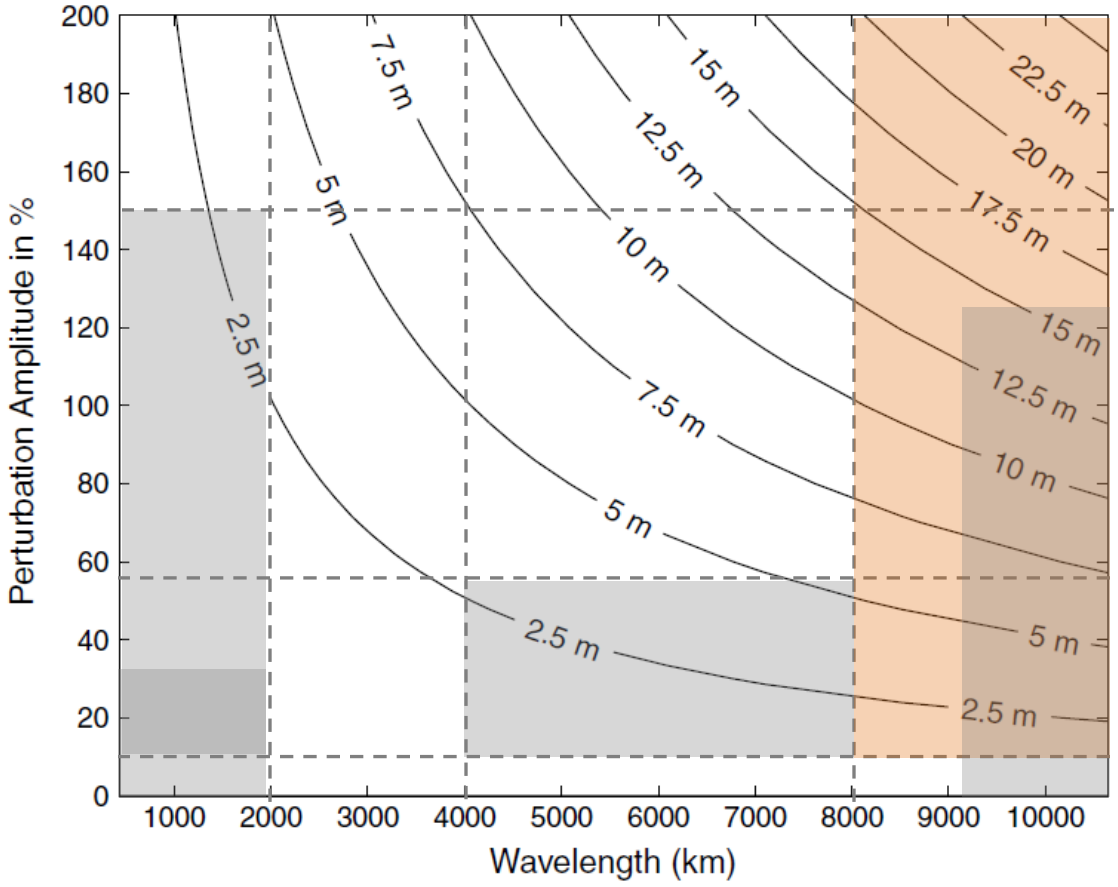
What is Satellite Drag?

Relative importance of various scales

What physical processes are important?

- **Large scale storm structures**
- Seasonal variability
- Density cell
- Cusp enhancement
- Non-hydrostatic effects

24 Hour Orbital In-Track Error at 400km Circular Orbit



[Anderson et al. 2009]

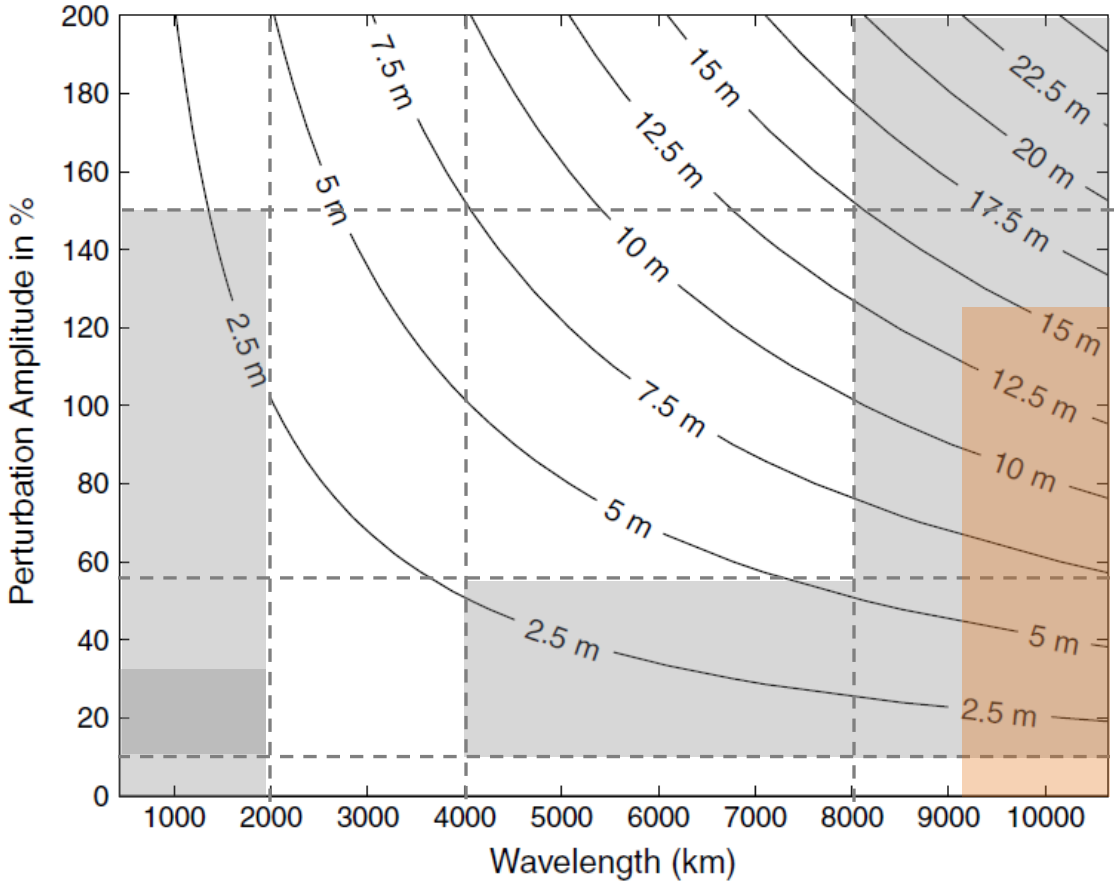
What is Satellite Drag?

Relative importance of various scales

What physical processes are important?

- Large scale storm structures
- **Seasonal variability**
- Density cell
- Cusp enhancement
- Non-hydrostatic effects

24 Hour Orbital In-Track Error at 400km Circular Orbit



[Anderson et al. 2009]

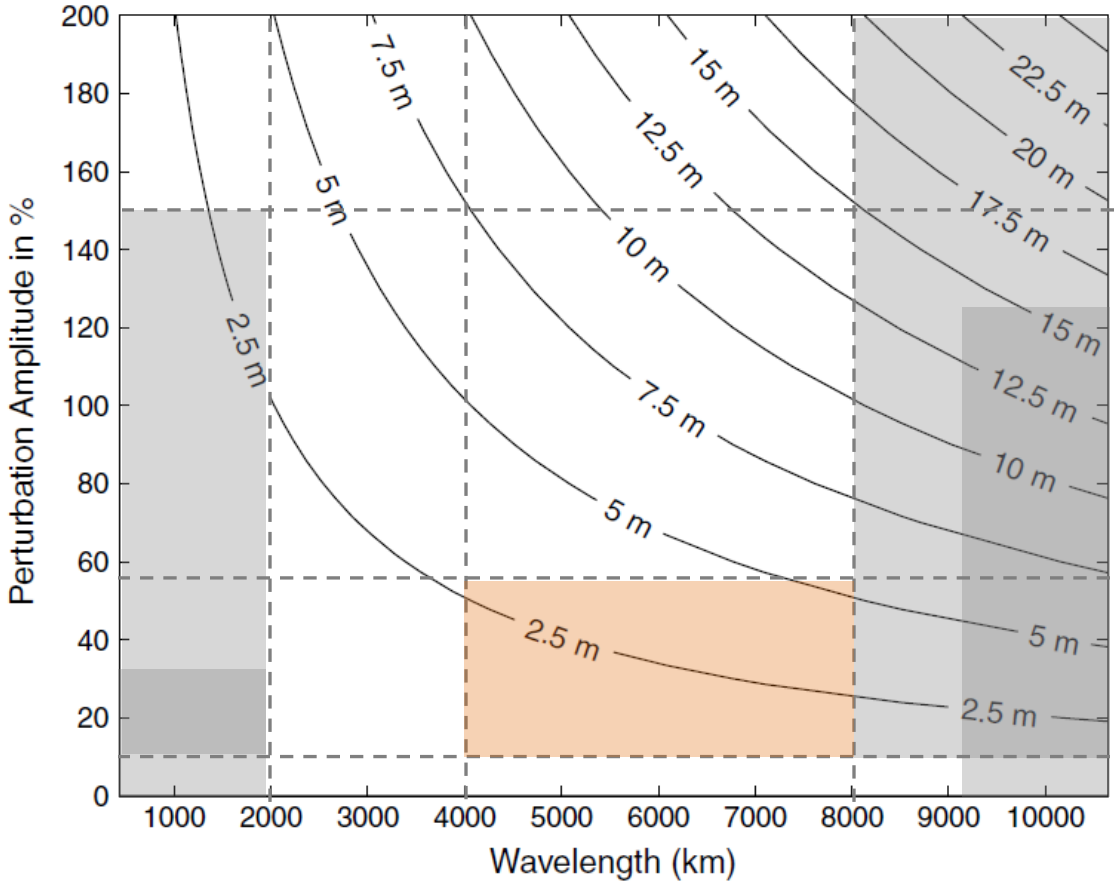
What is Satellite Drag?

Relative importance of various scales

What physical processes are important?

- Large scale storm structures
- Seasonal variability
- **Density cell**
- Cusp enhancement
- Non-hydrostatic effects

24 Hour Orbital In-Track Error at 400km Circular Orbit



[Anderson et al. 2009]

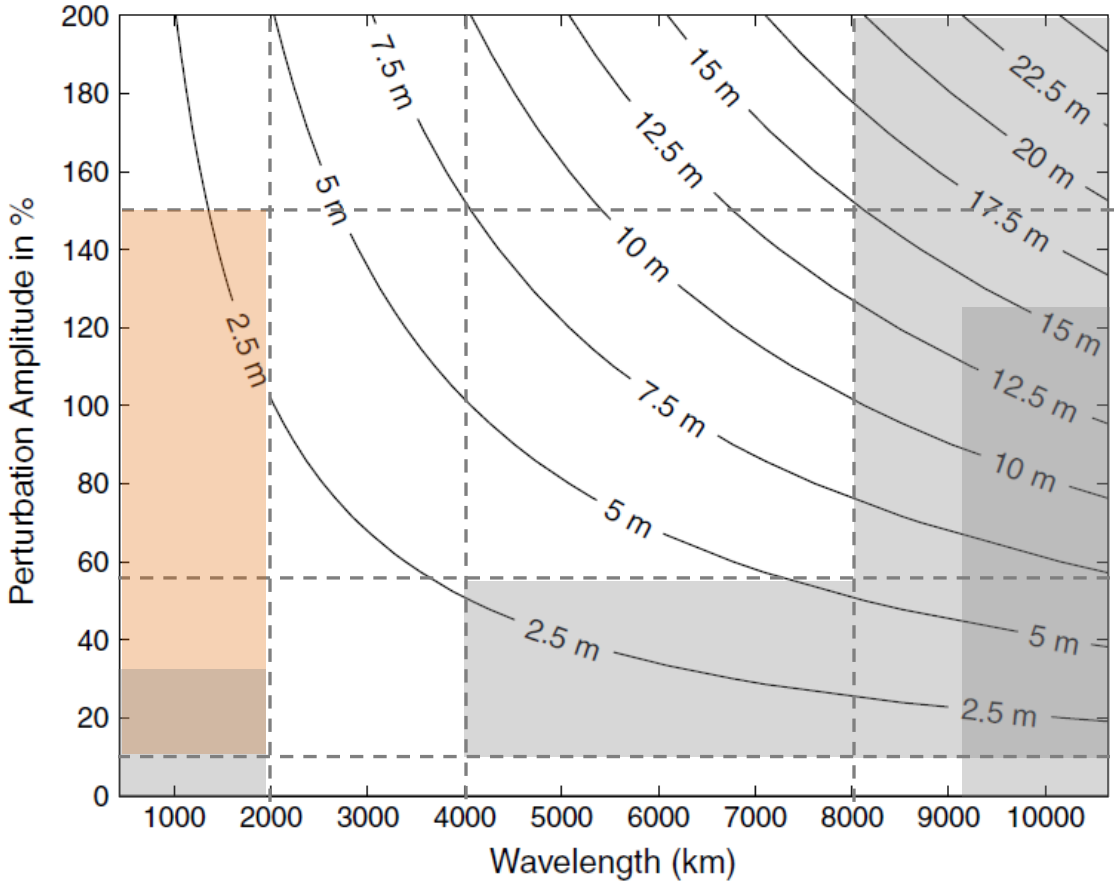
What is Satellite Drag?

Relative importance of various scales

What physical processes are important?

- Large scale storm structures
- Seasonal variability
- Density cell
- **Cusp enhancement***
- Non-hydrostatic effects

24 Hour Orbital In-Track Error at 400km Circular Orbit



[Anderson et al. 2009]

*not a persistent feature on these time scales

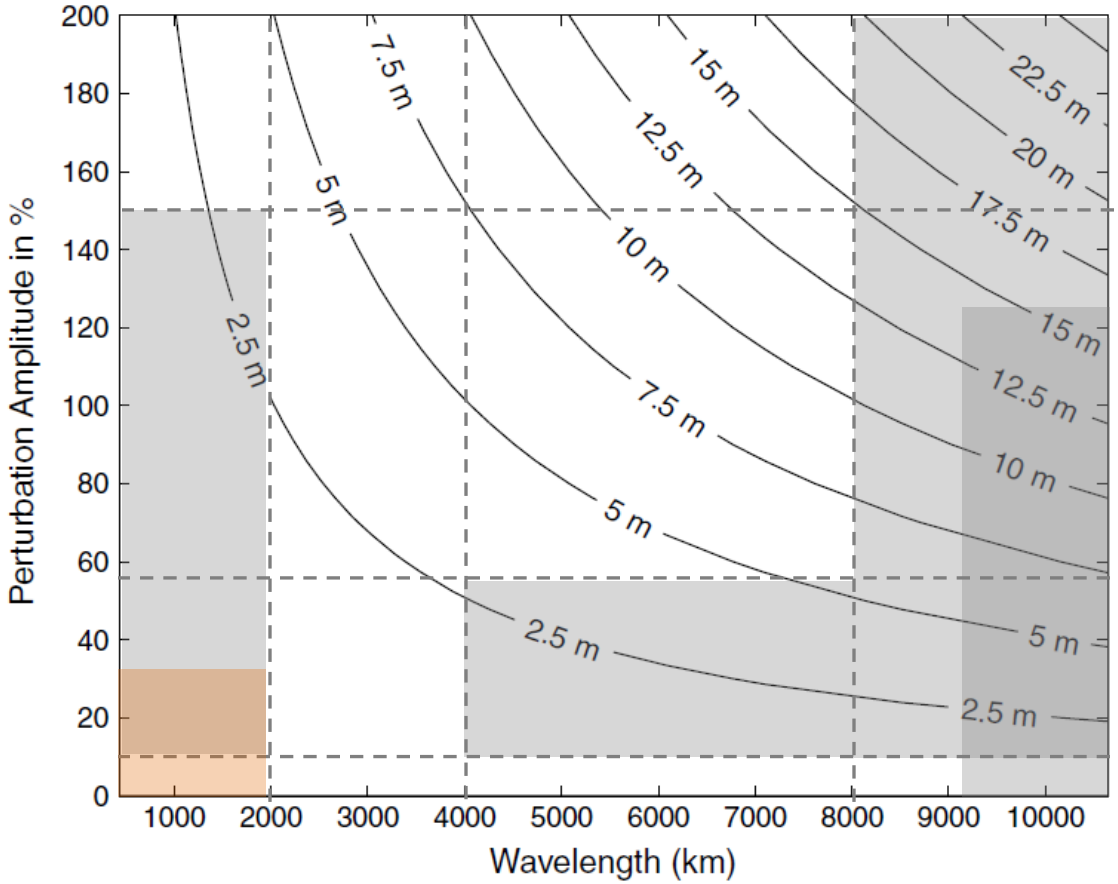
What is Satellite Drag?

Relative importance of various scales

What physical processes are important?

- Large scale storm structures
- Seasonal variability
- Density cell
- Cusp enhancement
- **Non-hydrostatic effects***

24 Hour Orbital In-Track Error at 400km Circular Orbit



[Anderson et al. 2009]

*not a persistent feature on these time scales